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Black Box SCR Modeling and Control for Small CI Engines

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Abstract:
Selective catalytic reduction (SCR) has become widely used to reduce NO_x emissions especially for medium and heavy duty CI engines, while lean NO_x traps (LNT) are a typical choice for light duty engines. In the field of small engines, SCR is usually not applied, because an expensive additional AdBlue supply is necessary and the emission limits can be also achieved with less complex methods. Nevertheless, if the engine is used as range extender of a hybrid electric vehicle, in engine-only operation it must also fulfill the Diesel emission legislation. There SCR is a sensible and maybe in view of future legislation only choice. A key problem of this choice, is that for small engines, typically the available space for the SCR is limited and leads to a strongly reduced storage capability of the catalyst. Some of the features of a small system render a purely data based approach feasible as system dynamics are faster and phenomenon like storage are less pronounced. Thus in this work a black box modeling approach is presented and combined with an NMPC strategy for closed loop SCR control. The proposed control strategy is validated in simulation and experiments on a testbench.

Keywords: Exhaust Aftertreatment, CI Engine Aftertreatment Control, Data based Modeling

1. INTRODUCTION

The emissions of modern Diesel engines are, besides the drivers torque demands and low fuel consumption one of the most challenging targets for combustion and aftertreatment control. To comply with the legislation limits (see e.g. Johnson (2013)), NO_x emission control for Diesel engines is not feasible without additional hardware. Possible solutions, which are already available, are a combination of a Diesel oxidation catalyst (DOC), a Diesel particulate filter (DPF) and Lean NO_x trap (LNT) or a selective catalytic reduction (SCR) system.
Whichever approach for exhaust aftertreatment is finally chosen, it requires a precise control to stay inside the legislation limits for the NO_x and PM, and in case of SCR system also NH_3 slip needs to be considered. In literature various investigations for modeling and control of the different devices can be found. For example SCR models are reaching form detailed high fidelity models (Sharifian et al. (2011)) to purely control oriented models (Zanardo et al. (2013)). Concerning the exhaust aftertreatment control, in Willems et al. (2007) and McKinley and Alleyne (2012) different SCR control schemes are discussed. For the DPF and the DOC, Jung et al. (2008) and Chatterjee et al. (2008) present modeling and experimental results, which are focusing on detailed DPF modeling and the aging phenomena of the DOC.
On contrary to these proposals in this work the behavior of the SCR and its optimal ammonia dosing control is investigated more in detail. A main reason is the considered engine setup in an SCR only configuration. The key element of an SCR catalyst is the reduction of NO_x to N_2 and H_2O under the presence of ammonia (NH_3). In order to store the ammonia in the SCR, different washcoat materials, typically consisting of copper (Cu) zeolite, iron (Fe) zeolite or vanadium (V), are used. But however, apart from variations due to the used materials (e.g. a Cu/zeolite SCR is less sensitive to HC poisoning than a Fe/zeolite (see Johnson (2013))), the basic reduction mechanisms for NO and NO_2 emission are the same for every SCR catalyst (see reactions (1),(2) and (3)).

$$4NH_3 + 3NO_2 \rightarrow \frac{7}{2}N_2 + 6H_2O \quad (1)$$

$$4NH_3 + 4NO + O_2 \rightarrow 4N_2 + 6H_2O \quad (2)$$

$$4NH_3 + 2NO + 2NO_2 \rightarrow 4N_2 + 6H_2O \quad (3)$$

In an SCR system, three main reduction mechanisms with different reaction times can be distinguished. While the reaction only with NH_3 and NO_2 (1) is relatively slow, the speed increases if NH_3 reacts with NO (2), which is the so-called standard SCR reduction. For the last reaction (3), the same amount of NO and NO_2 is required to react with NH_3. This reaction is again significantly faster than the second reaction, which only consumes NO. As a consequence, if a sufficient amount of NO_2 is available (usually after the DOC), the fastest reaction is primarily responsible to fulfill the overall conversion. Hence, a low NO_x conversion may be not only caused by the obvious reasons, such as a too low ammonia dosing or a too low SCR volume, but also due to an unbalanced NO/NO_2 ratio. In addition a uniform AdBlue spray injection its vaporization and the spatial distribution of ammonia are critical issues, because non uniformity is

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also a limitation factor of the reduction rate. Thus, the Adblue spray injection and its spray modeling is already widely discussed in studies (e.g. Stroem et al. (2009)).
To set up an appropriate SCR model for control, all these phenomena have to be considered, which requires in most cases a complex physical based modeling.

In this work,however, we propose a different, data based approach. This choice is motivated by a few assumptions and peculiar features of the specific system: In general, a data based approach is feasible if the main dynamics and reactions can be deduced from measurements and if phenomena, such as storage, are pronounced. By experimental NH_3 and NO_x measurements at the outlet of the considered SCR syste (for further details see Fig. 2) we determined that the ammonia storage of the SCR is sufficiently low and it is feasible to apply a purely data based black box approach without considering reduction mechanisms explicitly.
Apart from the chosen modeling approach also the highly nonlinear temperature dependency of the SCR reduction rate, included in the data based approach, needs to be considered by the afterwards applied dosing control, which promotes the use of a non linear control strategy. An intuitive choice seems to be the application of a non linear MPC strategy (see e.g. Magni et al. (2009)) because with recent developments of fast solvers and increased computational power also such complex systems can be solved in real time.

The rest of this work is structured as follows: First the experimental setup and the black box modeling assumptions for the SCR modeling are discussed. Afterwards the identification and validation results of the SCR model are presented. Then the model predictive controller framework is introduced and finally the proposed NH_3 dosing strategy and the results of the applied control strategy on the testbench are shown.

2. SYSTEM SETUP

The considered system is a 2 cylinder 1-liter Diesel engine with a maximum torque of 77 Nm at 1500 rpm and a maximum power of 26.4 kW at 3600 rpm. The engine is designed particular for range extender applications and equipped with a common rail injection system and turbocharging. Fig. 1 illustrates the main components of the testbench, the electrical dynamometer and the combustion engine.

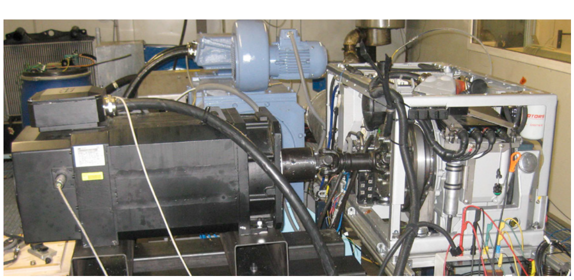

Fig. 1. Range extender testbench at the JKU labs

The used exhaust aftertreatment for this engine is an SCR only concept and consists of a copper ceolite SCR with an approximate volume of 0.87 liter. The system includes, besides the SCR, an Adblue reservoir, a pump and a dosing valve (accessed and controlled by pulse width modulation(PWM) with a minimum pulse length of 4 ms). The system is designed to ensure that the Adblue spray fulfills all required conditions for mixing and vaporizing uniformly to ammonia in the hot exhaust gas stream. The NO_x/NO, CO, CO_2 and O_2 emissions at the outlet as well as the inlet of the SCR were measured with a Horiba 7100 and the ammonia at the outlet of the SCR was measured with a Siemens LDS6. All data acquisition was done with Matlab XPC target, which includes required ECU signals, like the engine speed.

3. DATA BASED, BLACK BOX MODELING

As briefly discussed in the introduction, the biggest limitation, why typically a black box model cannot be used for modeling and control of SCR systems, is the fact that phenomena, which are not accessible within the recoded data, are not included in the model. Consequently, as first step the influence of the hidden phenomenon for the SCR, more precisely the ammonia storage capacity, needs to be analyzed. Therefore, a constant engine operation point ($n_{eng} = 2000\,\mathrm{rpm}$, $m_f = 22\,\mathrm{mg/cyc}$) with different Adblue dosing amounts is applied to the engine to analyze the storage capacity, shown in Fig. 2.

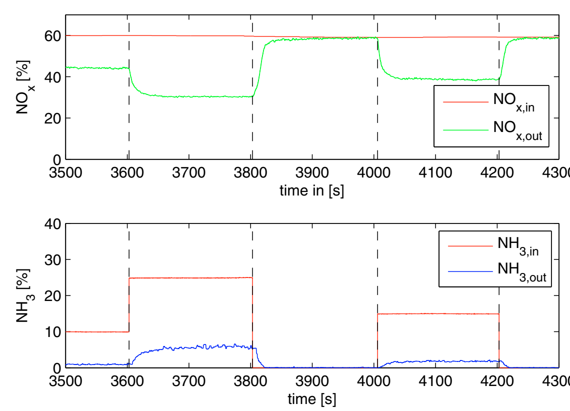

Fig. 2. Storage effect 0.87 liter SCR for the range extender application

In the lower plot of Fig. 2 it can be seen that the delay and rise times of the ammonia at the outlet of the SCR are relatively small compared to larger SCR catalysts, which are typically used for heavy duty applications (e.g. see Zanardo et al. (2013)). Consequently, it is assumed that the storage capacity has minor influence for this prototype SCR and a black box data based modeling approach is chosen. Additionally, it has to be noted that in this figure and also all following figures the NH_3 and NO_x amount have been scaled to the maximum occurring values.

4. SCR MODELING

Based on the previously discussed effects, the following assumptions for the data based modeling are made. The engine setup is without DOC and so, only the SCR standard reaction is taking place, which has to be considered for the objective function of the NMPC. To minimize the risk of only modeling the measurements instead of the system, the estimation of the model parameters for the black box model is performed in two steps: